Engine-Out Capabilities Assessment of Heavy Lift Launch Vehicles

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***Abstract*—Engine-out (EO) is a condition that might occur during flight due to the failure of one or more engines. Protection against this occurrence can be called engine-out capability (EOC) whereupon significantly improved loss of mission may occur, in addition to reduction in performance and increased cost.** [1,2]

A standardized engine-out capability has not been studied exhaustively as it pertains to space launch systems. This work presents results for a specific vehicle design with specific engines, but also uniquely provides an approach to realizing the necessity of EOC for any launch vehicle system design. A derived top-level approach to engine-out philosophy for a heavy lift launch vehicle is given herein, based on an historical assessment of launch vehicle capabilities. The methodology itself is not intended to present a best path forward, but instead provides three parameters for assessment of a particular vehicle.

Of the several parameters affected by this EOC, the three parameters of interest in this research are reliability (Loss of Mission (LOM) and Loss of Crew (LOC)), vehicle performance, and cost. The intent of this effort is to provide insight into the impacts of EO capability on these parameters. The effects of EOC on reliability, performance and cost are detailed, including how these important launch vehicle metrics can be combined to assess what could be considered overall launch vehicle affordability.

In support of achieving the first critical milestone (Mission Concept Review) in the development of the Space Launch System (SLS), a team assessed two-stage, large-diameter vehicles that utilized liquid oxygen (LOX)-RP propellants in the First Stage and LOX/LH2 propellant in the Upper Stage. With multiple large thrust-class engines employed on the stages, engine-out capability could be a significant driver to mission success.

It was determined that LOM results improve by a factor of five when assuming EOC for both Core Stage (CS) (first stage) and Upper Stage (US) EO, assuming a reference launch vehicle with 5 RP engines on the CS and 3 LOX/LH2 engines on the US. The benefit of adding both CS and US engine-out capability is significant. When adding EOC for either first or second stages, there is less than a 20% benefit.

Performance analysis has shown that if the vehicle is not protected for EO during the first part of the flight and only protected in the later part of the flight, there is a diminishing performance penalty, as indicated by failures occurring in the first stage at different times. This work did not consider any options to abort.

While adding an engine for EOC drives cost upward, the impact depends on the number of needed engines manufactured per year and the launch manifest. There is a significant cost savings if multiple flights occur within one year. Flying two flights per year would cost approximately $4,000 per pound less than the same configuration with one flight per year, assuming both CS and US EOC. The cost is within 15% of the cost of one flight per year with no engine-out capability for the same vehicle.

This study can be extended to other launch vehicles. While the numbers given in this paper are specific to a certain vehicle configuration, the process requires only a high level of data to allow an analyst to draw conclusions. The weighting of each of the identified parameters will determine the optimization of each launch vehicle. The results of this engine-out assessment provide a means to understand this optimization while maintaining an unbiased perspective.

[2] IEEEAC Paper #0000, Version 1, Submitted TBD, 2011

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Abstract— **A standardized engine-out capability (EOC) has not been studied exhaustively as it pertains to human-rated space launch systems. This work provides an approach to realizing the necessity of EOC for any launch vehicle system design, and also presents a systematic series of measures to assess the value of adding EOC to a specific system. A derived top-level approach to engine-out (EO) philosophy for a heavy lift launch vehicle is given herein, based on an historical assessment of launch vehicle capabilities. The methodology itself is not intended to present a best path forward, but instead provides three parameters for assessment of a particular vehicle.** [1,2]

Of the several parameters affected by this EOC, the three parameters of interest are reliability with sub-parameters of Loss of Mission (LOM) and Loss of Crew (LOC), vehicle performance, and cost. The intent of this effort is to provide insight into the impacts of EO capability on these parameters. The effects of EOC on reliability, performance and cost are shared, including how these important launch vehicle metrics can be combined to assess what could be considered overall launch vehicle affordability.

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1. INTRODUCTION

Engine-out is a condition that occurs during flight due to the failure of one or more engines. Mitigations to engine-out condition can be called engine-out capability (EOC), whereupon significant improvement to loss of mission (LOM) estimates is possible within reasonable performance and cost penalties.

During the early development activities of the Space Launch System (SLS), EOC was evaluated in support of achieving the first critical milestone (Mission Concept Review). A team assessed two-stage, large-diameter vehicles that utilized LOX/RP (liquid oxygen/kerosene) propellants in the first stage and LOX/LH2 (liquid oxygen/liquid hydrogen) propellant in the second stage as shown in Figure 1.

Evaluation of historical flight data allows an estimate of failures resulting in the loss of thrust from one or more engines during ascent. Here, it was seen that failure/shutdown of an engine was typically the consequence of events external to the engine proper (e.g., propellant feed system), as opposed to catastrophic failure of the engine itself. Regardless, the probability of engine failure due to all causes was examined due to its role in LOM estimates.

With multiple large thrust-class engines employed on the stages, protecting with EOC was found to be a significant driver to mission success. This analysis offers insight into the significance of inclusion of EOC for SLS, with extensibility to other heavy-lift launch vehicles.

[2] IEEEAC Paper #1176, Version 1, Submitted January, 2012

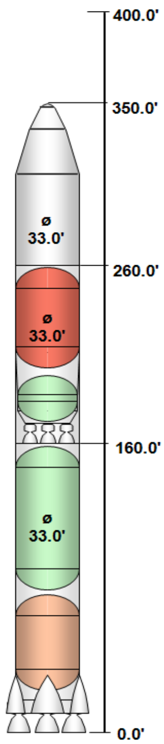

Figure 1. Reference Heavy Lift Launch Vehicle

It is the intent of this study to compile an abbreviated list of these common EO occurrences and predicate a procedure by which a launch vehicle system can weigh major factors to determine the criticality of EO capabilities. The study focuses on the impacts of EO capabilities as they affect reliability, vehicle performance, and cost.

2. Engine Failure Probability

When a vehicle failure is due to the engine, it is important to understand whether the failure mode is endemic to the engine system or externally induced. This section briefly discusses estimation of engine probability of failure as it pertains to this effort.

The largest indicator when determining the probability of engine failure is chamber pressure (Pc), as it directly correlates to delivered thrust. To realize increasingly higher levels of thrust, increased complexity engine cycles are required to achieve higher chamber pressures. Thus, as a system evolves from an expander cycle to a staged combustion cycle, the level of complexity increases (e.g., turbopump requirements), thereby worsening the predicted probability of failure. While Table 1 shows this general trend for hydrogen engines, the same trend holds for RP engines. Pressure-fed systems were not considered (only pump-fed), nor were other propellant combinations (e.g., LOX/methane).

Table 1. Estimated Probability of Engine Failure

Engine (LOX/LH2)	Cycle	Pc [psi]	Predicted Failure Rate (1 in N)
RL-10	Expander	350	1942
J-2X	Gas Generator	1340	1070
RS-68	Gas Generator	1450	756
SSME	Staged Combustion	2750	621

(Note: "1 in N" is the reciprocal of the probability value, assessed at 515 seconds total duration)

Engine-specific failure rates were obtained by examining the component-wise probability of catastrophic failure against a basis established by the Space Shuttle Main Engine (SSME) 2000 Quantitative Risk Assessment System (QRAS) study. Table 2 indicates how each engine component ranked in terms of individual probability of catastrophic failure on SSME Block II.

Table 2. SSME Block II Catastrophic Probability of Failure Drivers

Component	% of Total
High Pressure Fuel Turbopump	24.78%
Main Combustion Chamber	16.62%
Other Risk	16.23%
High Pressure Oxidizer Turbopump	14.52%
Nozzle	9.99%
Fuel/Hot Gas System	4.26%
Main Injector	4.01%
Pneumatic System	2.77%
Oxidizer System	1.80%
Low Pressure Oxidizer Turbopump	1.64%
Oxidizer Preburner	0.86%
Heat Exchanger	0.73%
Low Pressure Fuel Turbopump	0.42%
Actuators	0.38%
Powerhead	0.37%
Fuel Preburner	0.31%
Valves	0.30%

The detail underlying Table 2 is used directly in determining the "1 in N" statements given in Table 1 through a SSME Probabilistic Risk Assessment (PRA). Here, the QRAS contributions at the component level were appropriately aggregated to generate the engine system level probability of failure. The PRA accounted for SSME demonstrated reliability through application of a Bayesian statistical methodology with an "informed" prior distribution. The resulting estimate is then adjusted to contain a 30% margin.

To extend the analysis to other engine systems, government and industry subject matter experts arrived at scaling factors to apply at the component level. Therefore, it is recognized that assumptions on subsystem design can affect the estimated probability values when extending the stated basis to analysis of other engines. For example, an oxygen-rich staged combustion (ORSC) cycle is generally considered as having greater risk due to higher temperatures and material issues in an oxygen-rich application. Table 3 illustrates how the assumptions of robustness for engine subcomponents can affect estimates on an engine cycle that, in an uninformed case, would be construed as having a higher probability of failure.

Table 3. Engine Subcomponent Example

Engine	Fuel	Cycle	Pc [psi]	Predicted Failure Rate (1 in N)
RD-180	Kerosene (RP)	ORSC (LOX-rich)	3860	629
SSME	Hydrogen (LH2)	FFSC (Full-flow)	2750	621

In Table 3, the greater robustness (lower speed, less leakage potential) of the RD-180's high pressure fuel pump significantly minimizes the basis value derived against the SSME's high pressure fuel pump, resulting in nearly identical failure estimates for the engine system. For clarity, the catastrophic failure probability of the RD-180's high pressure oxidizer turbopump and hot gas system were assessed as 50% greater than the basis values due to the oxygen-rich environment.

In using these failure probabilities for assessing the need for EOC, the question of when to begin protection arises. Figure 2 is based on SSME test data and notionally illustrates the failure probability as a function of accumulated engine operation. Here, it is seen that "Catastrophic" failure is treated a constant risk and precludes EOC by definition. However, "Shutdown" is a decreasing function with the highest probabilities occurring early—"Infant Mortality." Given that liquid engines experience at least one acceptance test at full mission duration prior to flight, and are verified functioning in the final seconds prior to lift-off, one could make a convincing argument for a delayed EOC (e.g., lift-off + 20 seconds); thus, acknowledging the encroaching "Wear Out Risk".

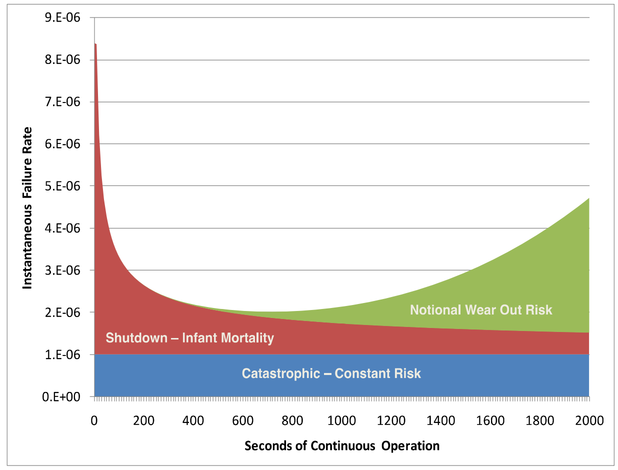

Figure 2. SSME Acceptance/ Testing Failures (Notional)

Further, failures of the vehicle system are often assumed to be directly caused by failures of the engine while this may not be the case. Table 4 shows data from a launch vehicle study [1] that assessed engine failures from 1980 through present day which indicates that the Main Propulsion System (MPS) has been the leading cause of failure, not the engine.

Table 4. Subsystem Interactions

		Manifesting Subsystem					
		Engine	MPS	GNC	Thermal Protectio n System	Staging	**Total**
Initiating Subsystem	Engine	3					3
	MPS	10	1		1		12
	Guidance, Navigation & Control (GNC)	2					2
	Unknown	1					1
	Structures					1	1
	Electronics	3		2			5
	Grand Total	19	1	2	1	1	**24**

Thus, engine-out may not just result from an engine that fails, but could also result from issues not endemic to the engine. There is always some probability of failure

whether the vehicle is protected against engine-out or not. With this in mind, the next step is to assess the affordability that EOC allows, in terms of reliability, performance, and cost.

3. SYSTEM EFFECTS OF EOC

The following discussion reflects the three figures of merit (FOM) assessed for EOC: reliability, performance and cost. Though the approach uses specific launch vehicle configurations, the philosophical discussion is intended to provide an approach to assess the overall effects of EOC on any given vehicle configuration.

Reliability

The reliability assessment performed by Safety and Mission Assurance (S&MA) found that the LOC and LOM numbers for a single stage EOC were roughly equivalent. The S&MA community chose to emphasize Core Stage (CS) EOC for crew safety. Employing CS EOC from lift-off through stage separation increases the likelihood of a successful tower clearance and provides the ability to delay an abort until the vehicle has passed beyond Mach 1 and when the vehicle would experience the maximum dynamic pressure. This would allow for a successful Multi-Purpose Crew Vehicle (MPCV) abort if needed. The following radar plots show the LOM and LOC impacts for 160 ft CS/100 ft Upper Stage (US) fixed frame vehicles, assuming 5 RP engines and 3 LOX/LH2 engines respectively (5-3), compared to 7 RP engines for the CS and 5 LOX/LH2 engines (7-5) for the US. These vehicles were analyzed in three flight scenarios: a CS engine failure, an US engine failure, and both a CS and US engine failure.

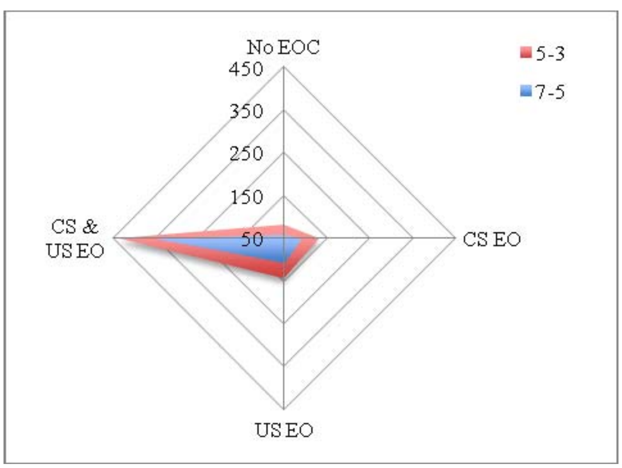

Figure 3. LOM EO Impacts

LOM and LOC are improved as EOCs are added to the vehicle, with the best result given when both stages employ EOCs. The 1 in N estimates given in Figures 3 and 4 indicate the probability of a LOM or LOC assuming various EOCs. The findings of the reliability modeling for LOM indicate that the two heavy lift launch vehicles performed similarly, with the 5-3 vehicle offering 29% more protection than the 7-5 vehicle sans EOC; 31% more protection assuming that just the CS is protected with EOC; 25% more protection assuming that just the US is protected with EOC; and an overall increase of 18% protection when both CS and US are modeled with EOC.

Generally, adding engines to either stage without any EOC reduces the overall LOM for the vehicle. The reduction is due to single engine reliability being a driver in the overall vehicle model. Another way to summarize this effect is that the complexity of the engines reduces the overall vehicle reliability.

Modeling shows that the LOM estimate of any particular configuration is roughly the same when either the US or CS is designed to have EOC. The LOM estimate for a stage exhibits a high degree of correlation between the product of the number of engines on a stage and the estimated burn time. As expected, when both the US and CS have EOC, the LOM estimate is far better than without EOC, in all cases, as shown in Figure 3 where the LOM estimate is approximately 1 in 400 for either vehicle when EOC is assumed for CS and US.

Figure 4 illustrates the LOC impact of EOC for the same three flight scenarios: a CS engine failure, an US engine failure, and both a CS and US engine failure. The 5-3 and 7-5 vehicles trend in the same direction with LOC improvement as EOCs are added to the vehicle. It can be seen that LOM is affected more than LOC, when the EOC is increased from No EOC to CS and US EOC.

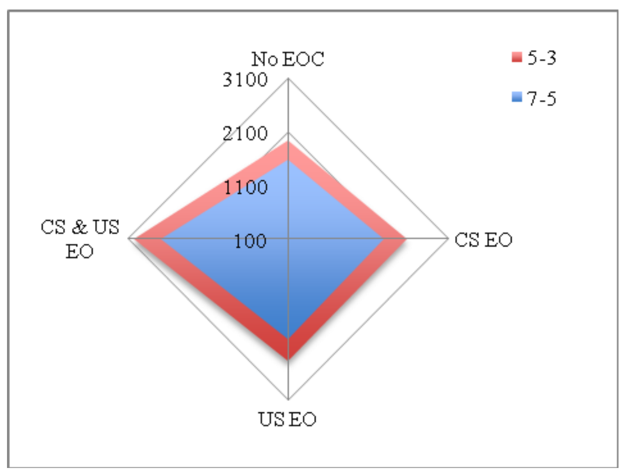

Figure 4. LOC EO Impacts

Modeling shows a significant shift in the failure modes based upon the type of EOC. The 5-3 vehicle showed that roughly 19% of CS engine failures and another 19% of US failure modes were uncontained engine failures. Uncontained engine failures have the lowest rate of successful crew abort for both the Core and Upper Stage. Therefore reducing the fraction of uncontained engine failures increases the probability of LOC, described as a 1 in N estimate, through a successful use of the abort system. For example, if the baseline of the 5-3 vehicle configuration had a 1 in 1000 LOC, then the 5-3 vehicle with Core Stage EOC would have roughly a 1 in 1107

LOC. Table 5 shows the relative improvement in the LOC estimate and percentage of uncontained engine failures by stage and combined for the four cases of a 5-3 configuration.

Table 5. Uncontained Engine Failures

Config.	LOC (~%)	Uncontained Engine Failure (as %)		
		Core Stage	Upper Stage	Total
No EOC	100	19	19	38
CS EOC	120	3	23	26
US EOC	122	23	1	24
CS & US EOC	154	4	1	5

Performance
The performance cost for protecting for engine-out varies widely. Each vehicle configuration has a nominal performance value and as such, the delta in Figure 6 shows that there is an overall smaller engine-out impact on the 7-5 launch vehicle. With EOC gradually added, the performance impact on the 5-3 vehicle increases until the loss is 52 tonnes of performance with both CS and US EO. Despite more engines on the 7-5 vehicle, the EO impact is less due to the greater overall nominal performance.

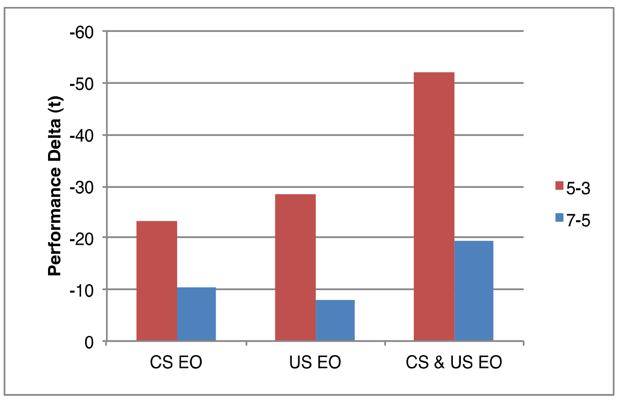

Figure 6. Vehicle Performance with EOC

To investigate the performance significance of CS engine failure through modeling, a single CS engine was failed at different predetermined times during flight. It was determined that the worst-case engine failure scenario occurred when removing an engine's contribution to performance for the entire flight of the stage. Propellant was removed from the CS tanks as a result of trade studies, in order to meet the 1.2 thrust-to-weight ratio liftoff requirement, while propellant was removed from the US to maximize payload. The modeling showed how much payload could be taken to a given orbit, assuming a CS engine was lost at a certain point in flight. The result was very little performance penalty if the vehicle is not protected for CS EO in the first part of flight (~first 20 seconds), especially if the payload mass is not maximized on the vehicle, suggesting that the target orbit could still be reached. This presents the option of challenging the need for EOC from the pad, since it is not likely that the launch would proceed if an engine did not ignite on the pad.

Cost
In addition to reliability and performance, launch cost is frequently a driving parameter that anchors a launch system to a schedule, and reflects the desires of the current political environment.

There is a one-time cost associated with choosing a launch vehicle. The Design, Development, Test and Evaluation (DDT&E) cost was derived assuming one rocket type, with the Production and Operations (P&O) cost dependent on the launch manifest. The cost differential is the number of engines manufactured annually.

EO capabilities were also assessed for multiple flights per year, as shown in Figure 7. For the 5-3 vehicle configuration launched once per year, the CS EOC increases the cost by nearly 25%, with only a slightly larger increase for US EOC. The largest decrement to cost is employing EOC on both stages, resulting in an 80% cost increase.

If the launch manifest assumes two flights per year, the initial cost for no EOC is cut by 40%, resulting in a lesser overall cost decrement when engines are added for EOC. Additional flights may be required for low marginal costs.

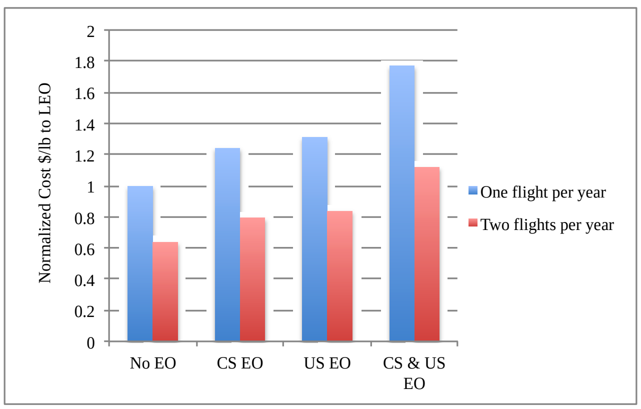

Figure 7. Multiple Flight "5-3" Vehicle Cost with EOC

Affordability
The three parameters discussed are the primary factors affected by EOC. However, the impacts to each parameter individually mean little if they are not integrated to assess affordability. For the reference vehicles used in this study, Figures 8 and 9 show that the EO impacts for CS and US are roughly equivalent in all four parameters, noting the P&O cost is higher to produce more engines for the CS.

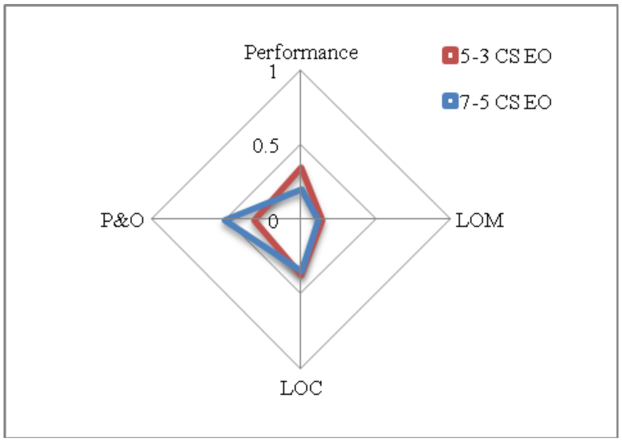

Figure 8. CS EO Impacts

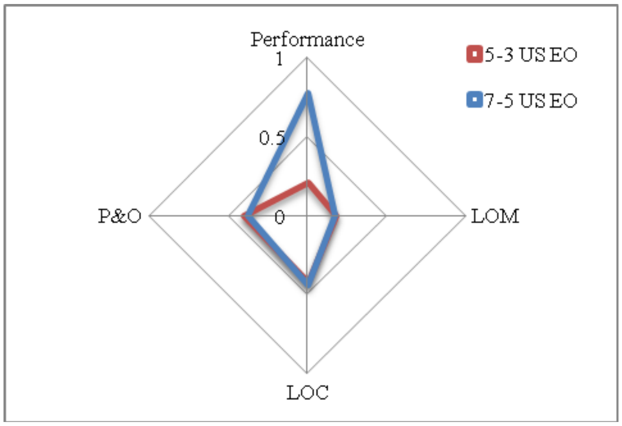

Figure 9. US EO Impacts

Figure 10 shows all of the parameters influenced by EOC, specific to the baseline 5-3 vehicle, but generally indicative of these parameters for any vehicle. LOM improves significantly by adding EOC on both CS and US, decreasing the risk by nearly a factor of five. The cost and LOC results are as expected, with P&O rising with the addition of engines, and the LOC value improving as EOC is added.

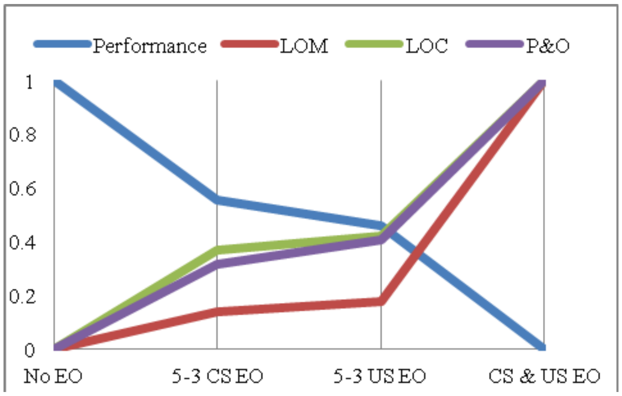

Figure 10. CS and US EO Impacts

It is clear that the biggest LOM benefit is CS and US EOC, since there is less than a 20% benefit of employing EO on either of the other stages. However, if the vehicle is optimized for reliability, it is up to the design team to determine how much the other parameters may be compromised.

4. Conclusion

The presented approach addressed the need for an EOC assessment as it pertains to a human-rated space launch system. While the numbers given in this paper are specific to a certain vehicle configuration, the process requires only a high level of data to allow an analyst to draw conclusions. The weighting of each of the identified parameters will determine the optimization of each launch vehicle. The results of this engine-out assessment provide a means to understand this optimization while maintaining an unbiased perspective.

Optimization on certain metrics will affect the choice for EOC. In this study, it was determined that LOM results improve significantly when assuming EOC for both CS and US. EOC on either stage will improve LOC and LOM, but EO on the CS has additional benefits. Additionally, performance analysis showed that if the vehicle is not protected for EO during the first part of the flight and only protected in the later part of the flight, there is a diminishing performance penalty, as indicated by failures occurring in the first stage at different times. This work did not consider any options to abort. The benefit of adding both CS and US EOC is significant from a reliability perspective, and while adding an engine for EOC drives cost upward, the impact depends on the number of engines to be manufactured per year with a given launch manifest. Once a vehicle configuration and manifest is selected, cost trades can be performed against safety and mission to determine EOC requirements.

The next step is to decide when to enact EOC during build. Implementation may be during the design of the MPS, during the installation of an additional engine at Michoud Assembly Facility (MAF), or prior to shipment to Cape Canaveral.

The intent of the study is to allow this type of EO assessment to extend to other launch vehicle systems, including heavy-lift and commercial vehicles. Overall, the weighting of each of the identified parameters determines the optimization of each launch vehicle. The way in which a vehicle is optimized is a significant factor when assessing for EOC.

5. Forward Work

The approach presented for this EOC assessment was purposefully designed with a top-level perspective, and as such there are several areas that would require further efforts.

Other analysis models may be generated to assess abort conditions that should conduct tradeoffs between successful missions versus successful aborts. In addition, there are multiple ways for guidance to respond which

would increase the chance of launch success and result in lower performance penalty. Evaluating emergency throttle settings run during contingency situations would also offer insight into response time and help to dictate the need for additional engines and thus EOC.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the SLS RAC Team 2 as well as many others for their contributions and suggestions for this study.

The material in this paper is also based upon work supported by NASA under Universities Space Research Association (USRA) award No. NNM08AA04A.

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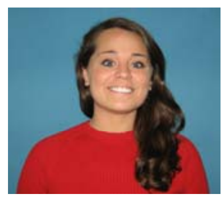
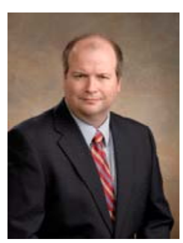
BIOGRAPHIES

Jon Holladay serves as the Ares V Vehicle Integration Manager for the Ares Projects Office at NASA’s Marshall Space Flight Center (MSFC), where he is certified as Level 4 Systems Engineer and a Level 3 Project Manager. He holds a Bachelors and a Masters degree in Mechanical Engineering from the University of Alabama and has completed the Legislative Studies Certificate Program at Georgetown University. Mr Holladay has over 20 years of experience involving human rated spacecraft and launch vehicle systems ranging from the International Space Station to the Constellation Program. Prior to assuming the role as Vehicle Integration Manager for Ares V, Mr. Holladay served as the Chief Engineer for the NASA MSFC’s Exploration and Space Operation Division.



Keithe Baggett provides support to the SLS Project Office at NASA MSFC as a Systems Integration Engineer. She holds a Bachelors and a Masters degree in Aerospace Engineering from Worcester Polytechnic Institute and Boston University, respectively. Ms. Baggett has completed internships at several companies, including GE Aircraft Engines, Zero Gravity Corporation, Miltec, and Orion Propulsion. Since joining MSFC in January, she has been involved in Ares V vehicle integration technical analysis, exploring vehicle extensibility options, and generating documentation to detail conceived vehicle and mission designs. She is currently an engineer at Zero Point Frontiers Corporation.

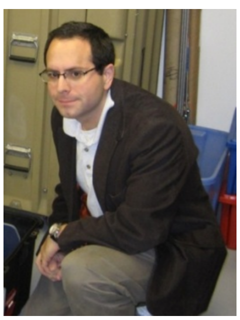


Mr. Chad Thrasher is currently assigned to NASA Headquarters in the Programmatic & Strategic Integration group in the Human Exploration & Operations Mission Directorate as a Project Executive. He began his career with NASA as a contractor to Marshall Space Flight Center (MSFC) in Huntsville, Alabama, in 1996.

Between 2006 and 2009, Mr. Thrasher served as the Lead Safety Engineer for the Ares I Vehicle Integration Project, at the MSFC, supporting the S&MA Directorate. From July 2009 until September 2011 he was the Deputy Manager of the Crew Safety and Reliability WBS for the Ares I Vehicle Integration (VI) Project at MSFC.

He has served as the president of the Tennessee Valley Chapter of the System Safety Society and received the local chapter’s Engineer of the Year award in 2007 and the Manager of the Year award in 2009.

Scott Bellamy is a liquid propulsion engineer supporting the Exploration Systems Liaison Office and the SLS Liquid Engine Office at MSFC. Formerly an officer in the US Air Force, he is an accredited DoD Space Professional and holds DoD Acquisition Professional certifications in Systems Planning, Research, Development, and Engineering; Program Management; and Test. Across 27 years of experience, he posses 19 concurrent years in NASA and DoD's space-related initiatives as acquisition engineer, rocket propulsion test engineer, program/project manager, SE&I practitioner, and modeling & simulation analyst. Mr. Bellamy holds a Bachelors degree in Mechanical Engineering from the University of Arizona and a Masters degree in Operations Research from the Air Force Institute of Technology. Prior to retiring from the Air Force, he served at MSFC as the Ares V Core Stage Engine Manager. He is currently employed at Booz Allen Hamilton.



Stuart Feldman is a founder and owner of Zero Point Frontiers Corp, an engineering firm in Huntsville, AL specializing in design integration, systems analysis, architecture development, and decision management. Mr. Feldman is providing engineering support to NASA exploration systems and heavy lift launch vehicle activities as well as to the NASA Constellation Program. Mr. Feldman represented the Launch Vehicle team on the development of NASA Mars Design Reference Architecture 5.0. Mr. Feldman has prior program experience on Bigelow Sundancer while at Orion Propulsion, Crew Exploration Vehicle at Northrop Grumman, and Mars Exploration Rover and C/NOFS at The Aerospace Corporation. Mr. Feldman holds a B.S. in Aerospace Engineering and a Masters of Engineering in Space Systems, both from the University of Michigan, as well as an MBA from Pepperdine University, and is currently pursuing a Ph.D. in Systems Engineering at University of Alabama in Huntsville.

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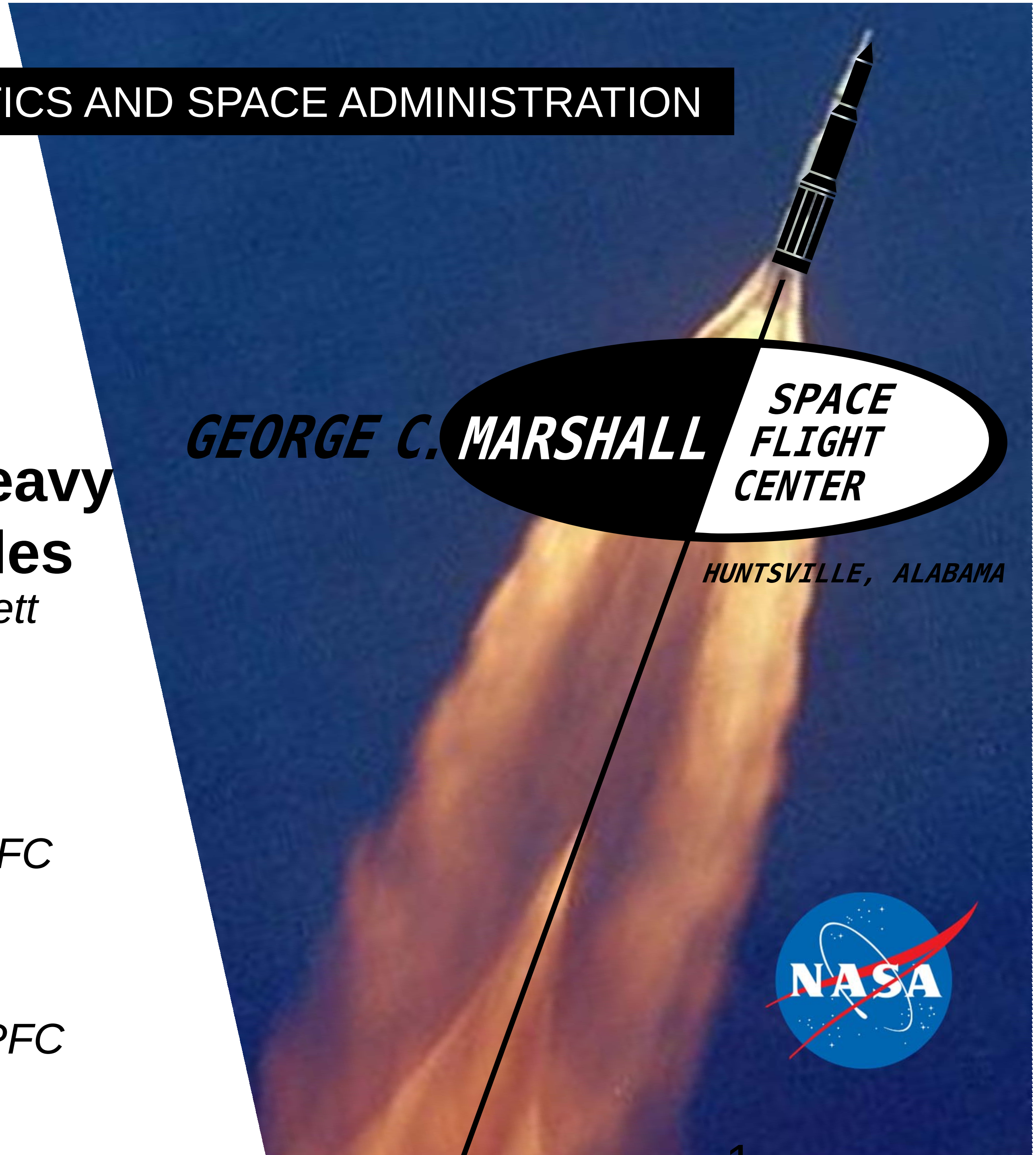

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3.4.2012

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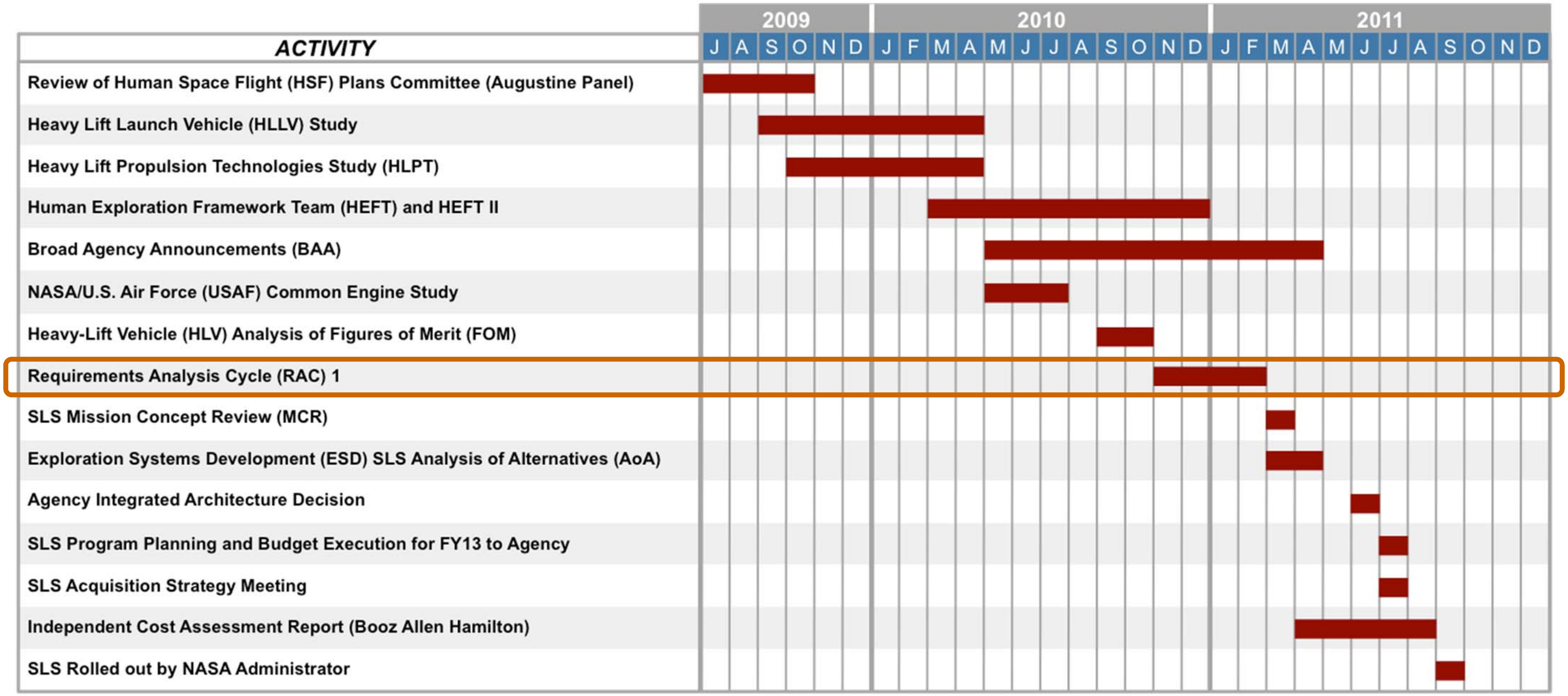
Presentation Summary

- **Introduction**
  - Objective
  - Background/Historical Perspective
- **Engine Failures**
  - Probability of Engine Failure
  - Engine-Out Drivers
- **System Effects of Engine-Out Capabilities**
  - Reliability
  - Performance
  - Cost
  - Affordability
- **Summary of Results**

Preamble

- **NASA assessed many potential options for the Space Launch System which could meet the budget, schedule, and performance requirements as given in the NASA Authorization Act of 2010**
- **A series of in-depth technical and business-case analyses & studies were conducted by government and industry experts**
- **The SLS architecture currently in design and development was the sole solution that met the following major requirements:**
  - First launch in 2017
  - Use current contracts, workforce and infrastructure
  - Very constrained budget
- **The results presented in this paper and presentation by Requirements Analysis Cycle 1, Team 2 are given in historical context only. This is not a revisiting of the decision made by NASA**

SLS Roadmap

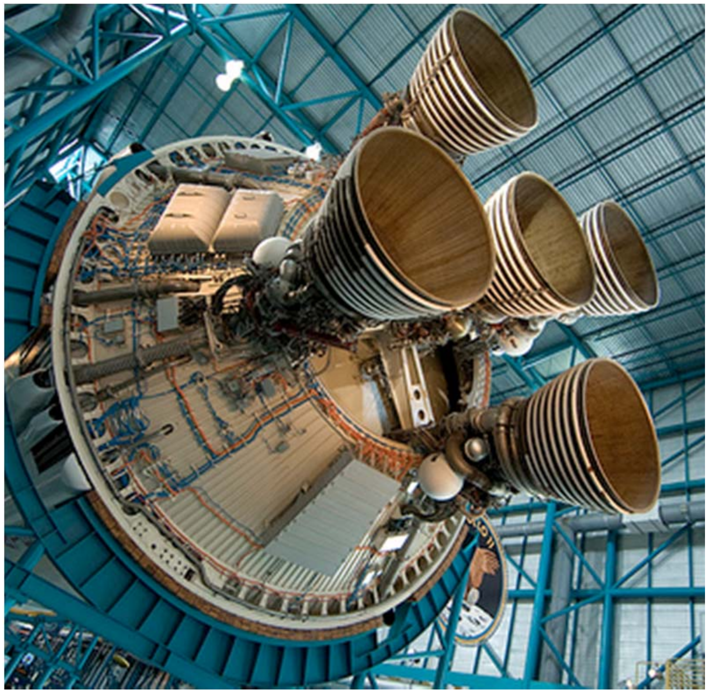


ACTIVITY
2009
2010
2011
J A S O N D
J F M A M J J A S O N D
J F M A M J J A S O N D
Review of Human Space Flight (HSF) Plans Committee (Augustine Panel)
Heavy Lift Launch Vehicle (HLLV) Study
Heavy Lift Propulsion Technologies Study (HLPT)
Human Exploration Framework Team (HEFT) and HEFT II
Broad Agency Announcements (BAA)
NASA/U.S. Air Force (USAF) Common Engine Study
Heavy-Lift Vehicle (HLV) Analysis of Figures of Merit (FOM)
Requirements Analysis Cycle (RAC) 1
SLS Mission Concept Review (MCR)
Exploration Systems Development (ESD) SLS Analysis of Alternatives (AoA)
Agency Integrated Architecture Decision
SLS Program Planning and Budget Execution for FY13 to Agency
SLS Acquisition Strategy Meeting
Independent Cost Assessment Report (Booz Allen Hamilton)
SLS Rolled out by NASA Administrator

Introduction

- **Objective:** A derived approach to EO philosophy based on an historical assessment of launch vehicle capabilities

- **Background**
  - Historical Perspective (Engine-Out Capable Missions)



Apollo 6
Apollo 13
STS-51-F
STS-9

Subsystem Interactions by Failed Stages

Subsystem reliability is not the only driver for launch success

- The interactions/dependencies of critical subsystems is very important--over half of all failures propagate to a different subsystem
- Liquid stages have more tightly coupled systems than solid stages

Initiating Subsystem	Manifesting Subsystem: engine	MPS	GNC	TPS	staging	Total
engine	3					3
MPS	10	1		1		12
GNC	2		0			2
unknown	1					1
structures					1	1
electronics	3		2			5
Grand Total	**19**	**1**	**2**	**1**	**1**	**24**

"Liquid and Solid Propulsion, 2011"
Safety & Reliabiility
Donovan L. Mathias, Ph.D
NASA ARC

Integrated propulsion system may manifest the failure, but the initiating aspect may be elsewhere

Engine $P_{failure}$ Drivers

- **Combustion cycle is most prominent influencer to P_f within a propellant combination (LOX/RP, LOX/H2…)**

Engine (LOX/H2)	Cycle	Pc [psi]	Pred Failure Rate (1 in N)
RL-10	Expander	350	1942
J-2X	Gas Generator	1340	1070
RS-68	Gas Generator	1490	756
SSME	Staged Combustion	2750	621

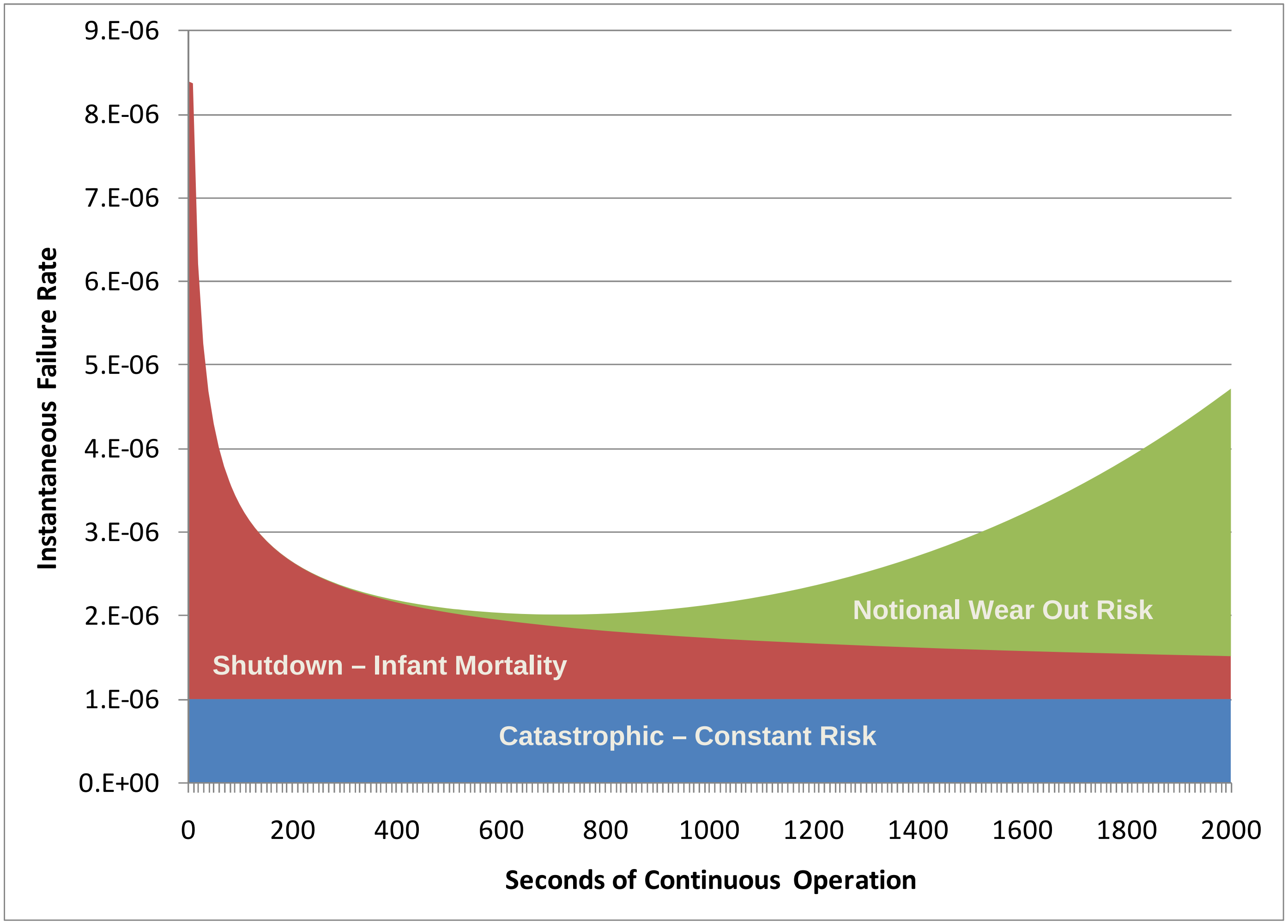
  - More complex cycle needed for higher pressures
  - Subsystem design margin influences P_f estimate
    —RS-68 turbopumps penalized heavily compared to J-2X

Example: Lox-rich Staged Combustion (ORSC) typically seen as having greater risk due to higher temps and materials compatibility issues, but…
—Assumed robustness of subcomponents can influence the difference

Engine	Fuel	Cycle	Pc [psi]	Pred Failure Rate (1 in N)
RD-180	Kerosene	ORSC (Lox-rich)	3860	629
SSME	Hydrogen	FFSC (Full-flow)	2750	621

Engine $P_{failure}$ Modes

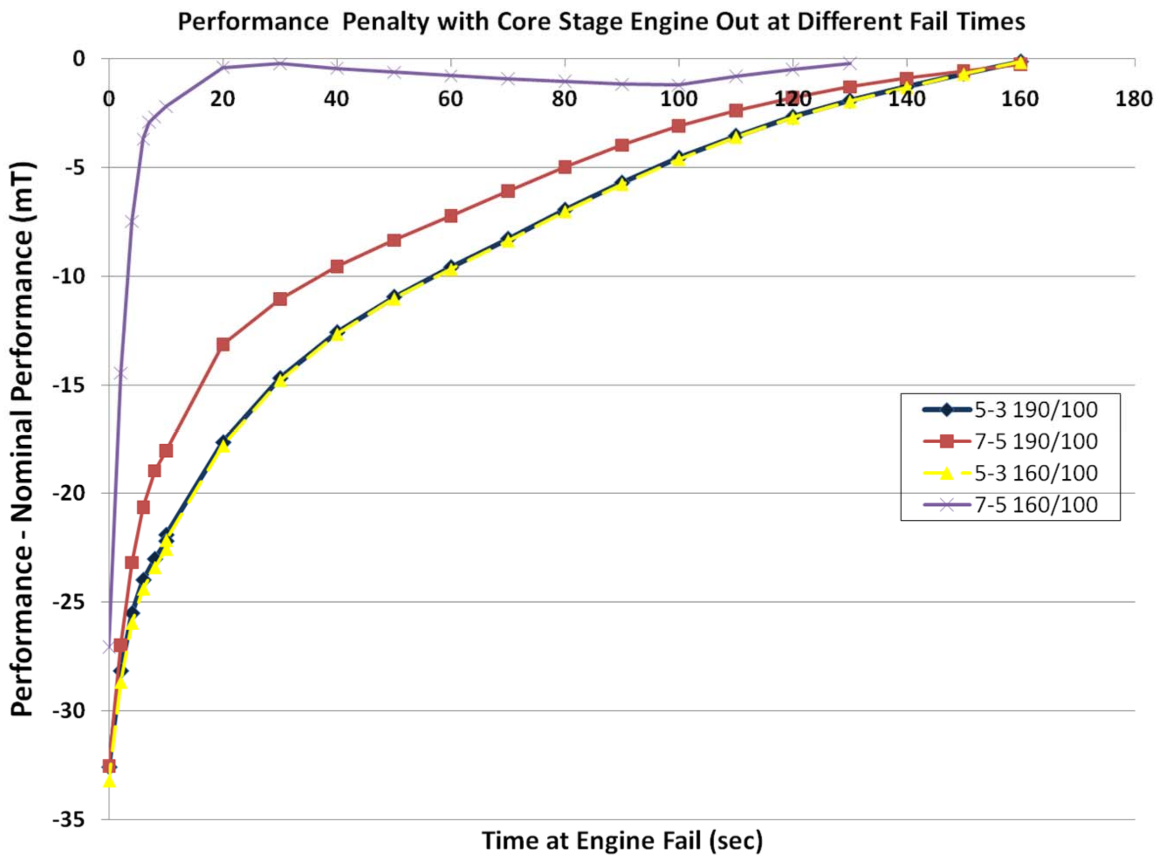
- ♦ **SSME Acceptance/Green-run testing filters failure modes**



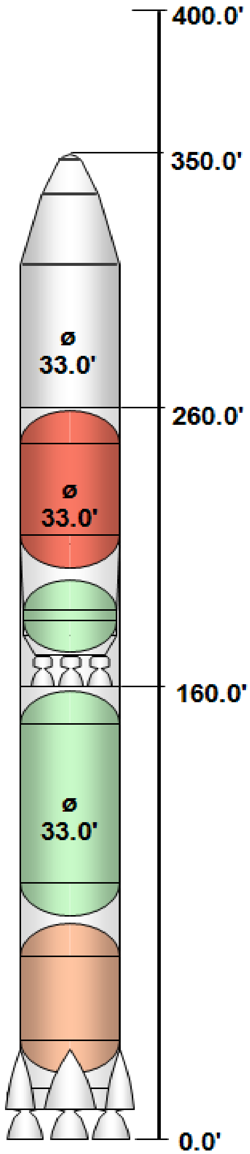
Engine $P_{failure}$ Core Stage

- **A single Core Stage engine was failed at different predetermined times during flight**

- **160'/100' 7-5 nominal case included throttling to alleviate high max q; When an engine failed the remaining engines were throttled up.**



System Effects of EOC

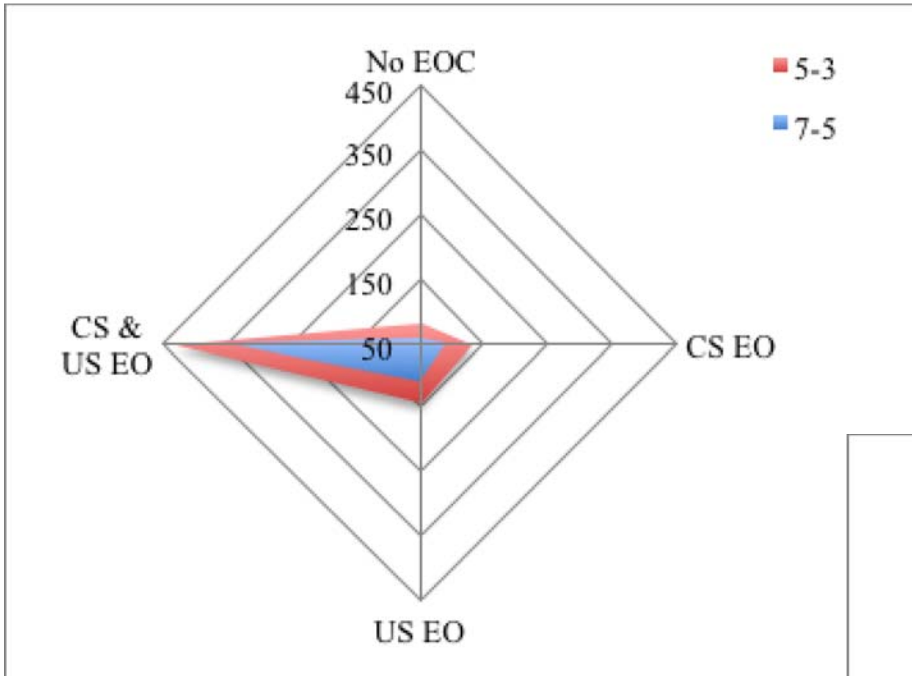


Reference Heavy Lift Launch Vehicle

- **Reliability**
- **Performance**
- **Cost**

Affordability

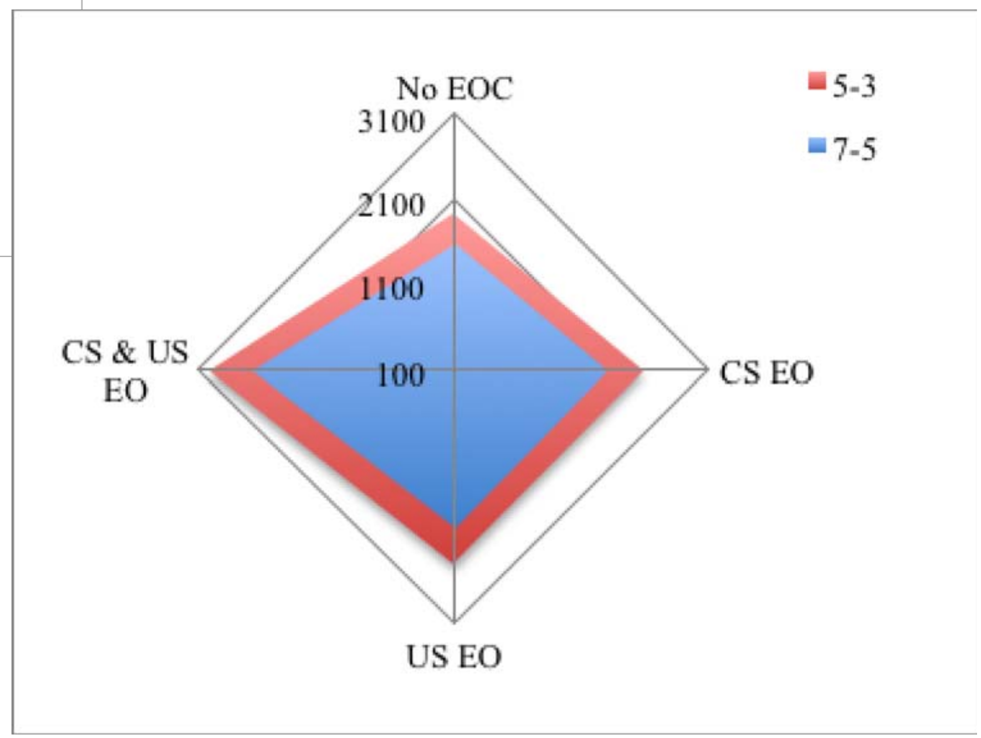
System Effects of EOC: Reliability



(Units given as 1/N probability)

Config.	LOC (~%)	Uncontained Engine Failure (as %)		
		Core Stage	Upper Stage	Total
No EOC	100	19	19	38
CS EOC	120	3	23	26
US EOC	122	23	1	24
CS & US EOC	154	4	1	5

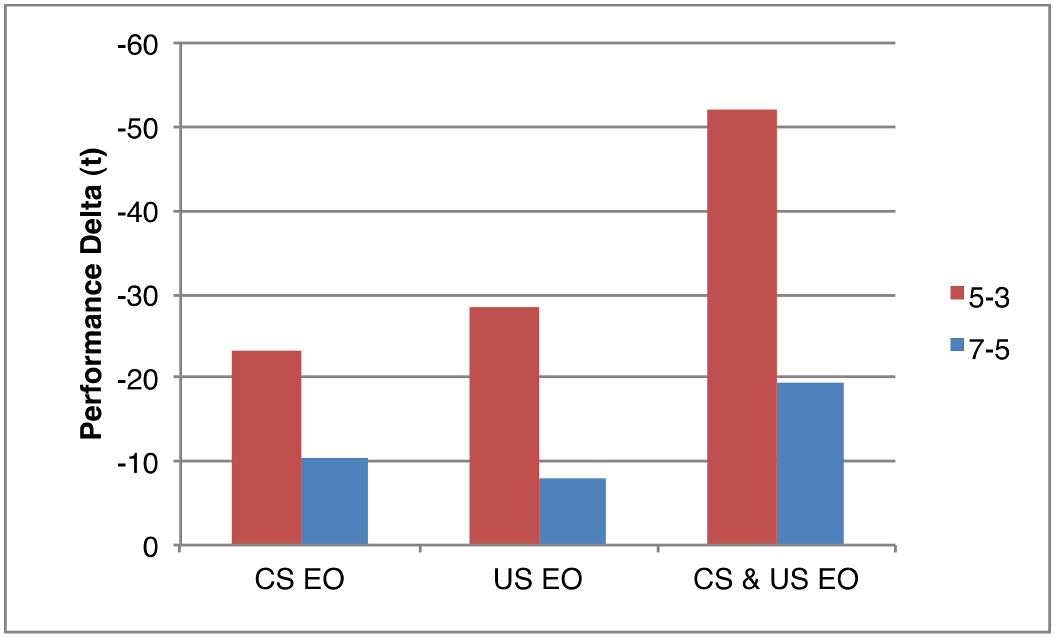
- **FF vehicles run with EO cases**
  - No Engine Out
  - Core Stage Engine Out
  - Upper Stage Engine Out
  - Both



System Effects of EOC: Reliability Cont'd

- **Core or 2nd stage EOC roughly equivalent LOC/LOM**
- **Core EOC from lift off selected**
  - Increases likelihood of successful MPCV abort if needed
    - Pushes past Mach 1 and Max-Q
- **Engine throttling allows one configuration for multiple payloads – increasing the ability to track overall vehicle performance**

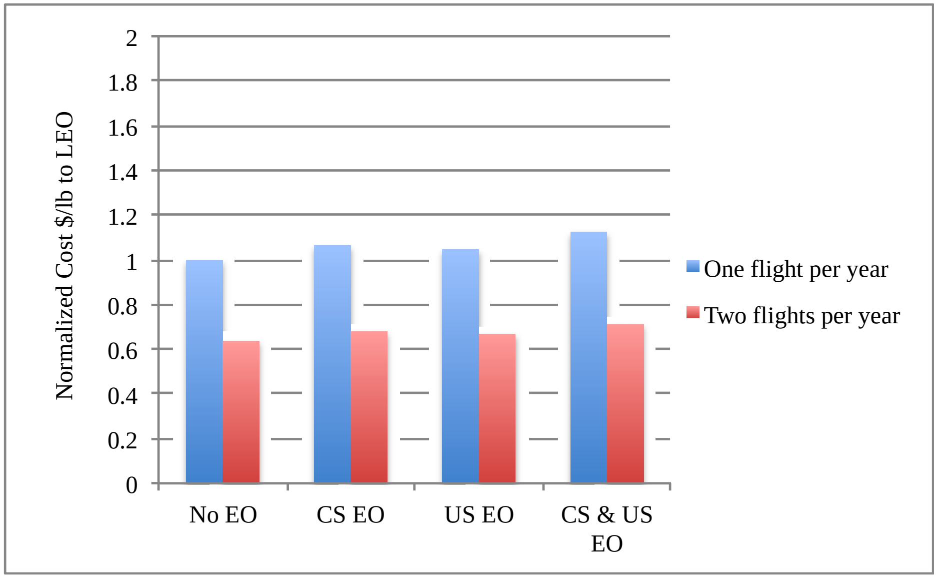
System Effects of EOC: Performance



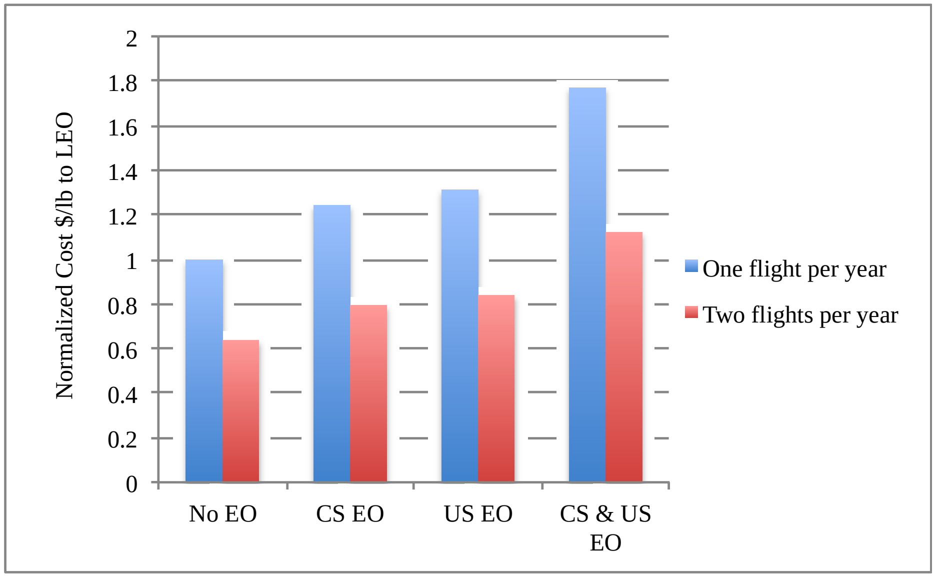
- **FF vehicles run with EO cases**
  - No Engine Out
  - Core Stage Engine Out
  - Upper Stage Engine Out
  - Both
- **Delta is the engine out case minus nominal performance.**
  - Different nominal performance for each individual vehicle configuration.
- **Engine out impact is smaller on the 7-5**

System Effects of EOC: Cost

“7-5” Vehicle

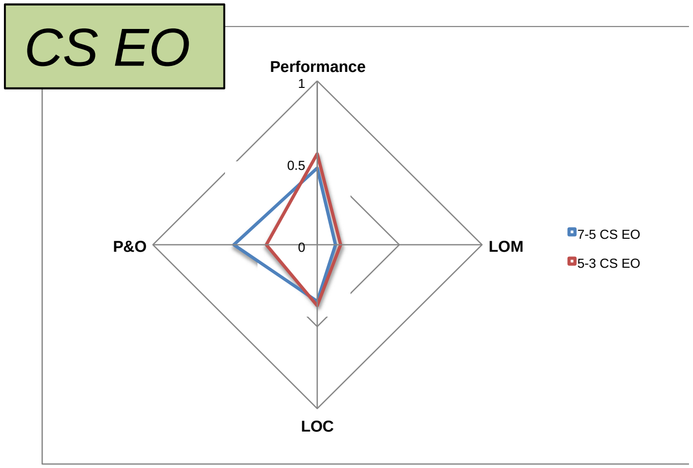


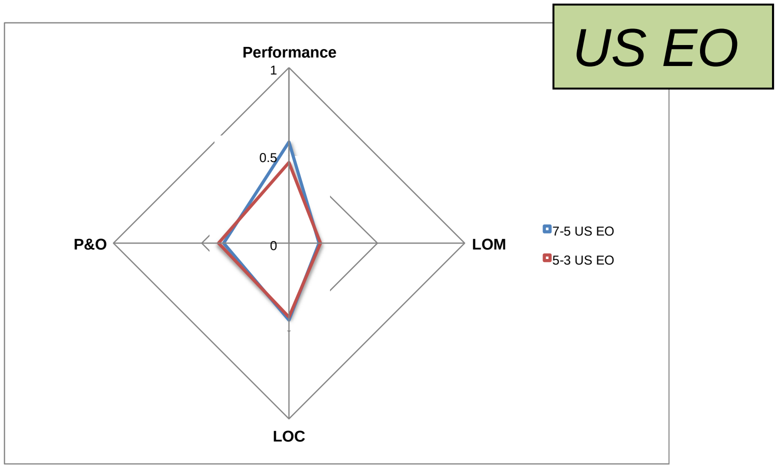
“5-3” Vehicle

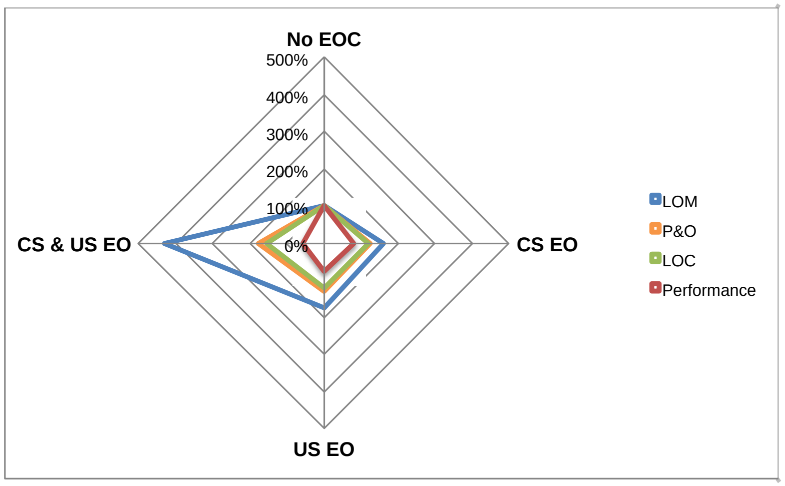


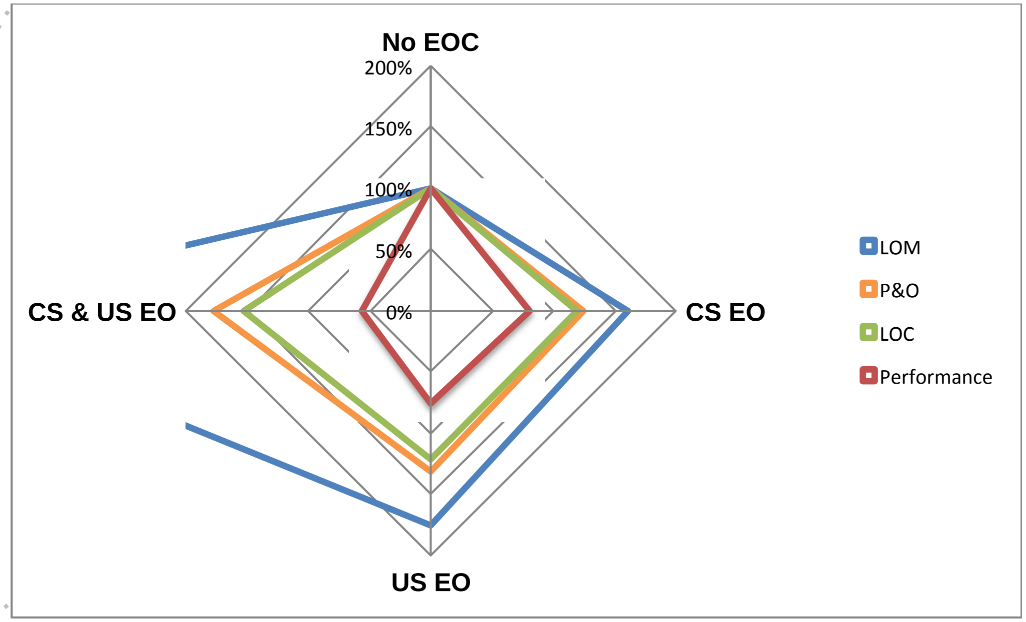
- **One DDT&E assuming one rocket type is built *(e.g. 5-3 instead of 7-5)***
- **P&O depends on the manifest**
- **The cost differential is the number of engines manufactured annually**

System Effects of EOC: Affordability (5-3 LV)



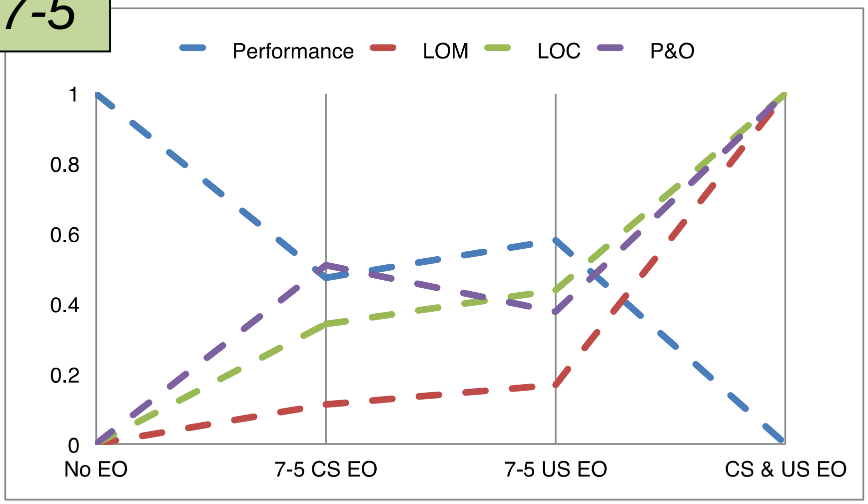




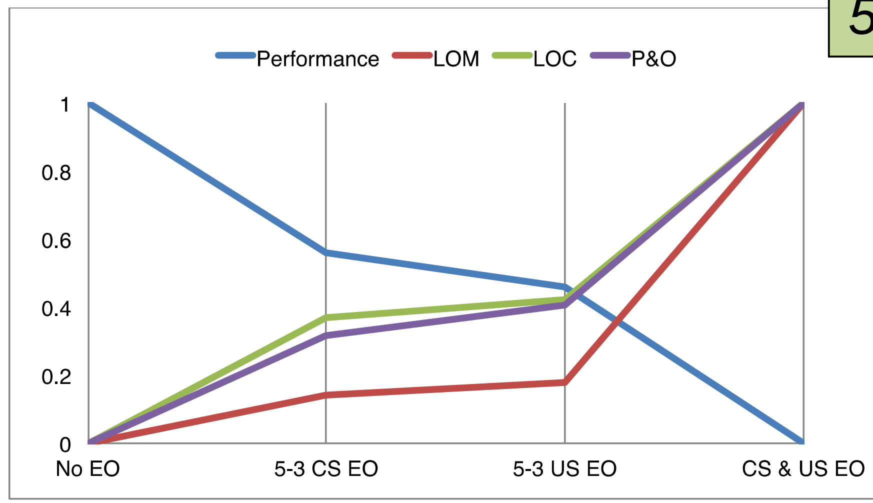


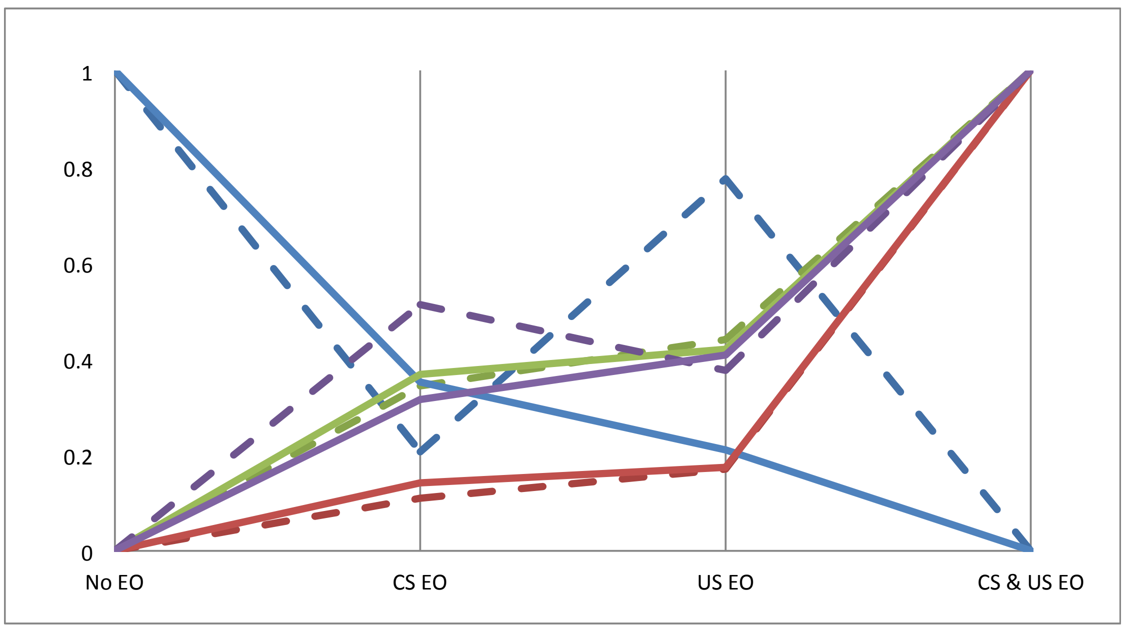
System Effects of EOC: Summary

7-5



5-3





When To Design for EOC

- ♦ **Decide to design for EOC**
- ♦ **Decide when to enact EOC during build**

Reliability
Performance
Cost

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.
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Design MPS with blank-plate
Install additional engine at MAF during assembly/build
Protect for EO prior to shipment to the Cape
Protect for EO after shipment to the Cape

.
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Design for EOC and choose when to implement

Findings

1. EOC (Both CS and US) offers a significant LOM improvement

2. If vehicle is not protected for EO in the first part of flight and only protected in the later part of flight, there is very little performance penalty

3. Mission and crew safety should be evaluated to determine EOC requirements once a specific vehicle configuration and mission are selected.

Summary of Results

Cost

- Number of engines manufactured per year is the cost driver, since DDT&E and P&O will remain the same for each engine

Reliability

- Engine-out capability on either stage will improve LOC/LOM, but EO on the Core Stage has additional benefits

Performance

- 7-5 engine out has smaller impacts than the 5-3, especially for an US engine out
- New data indicates that most failures originate in the MPS not in the engine, but manifest in the engine.

Conclusion: Affordability is dependent upon the number of engines per vehicle; As engines are added, LOC/LOM & Performance improve while Cost increases